Performance of the First Year of the Completed US Operational Deep-Sea Tsunameter Network

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***Abstract*-In March 2008, the National Oceanic and Atmospheric Administration's (NOAA) National Data Buoy Center (NDBC) completed the deployment of the full 39-station network of deep-sea tsunameters bolstering the U.S. tsunami warning system. This vast network of 39 stations provides coastal communities in the Pacific, Atlantic, Caribbean and the Gulf of Mexico with faster and more accurate tsunami warnings. The tsunameters employ the patented technology of the second generation Deep-ocean Assessment and Reporting of Tsunamis (DART® II).**

A full year of operating the completed network provided a host of challenges and accomplishments. Data availability statistics missed the operating goal of 80%, primarily due to a rash of mooring failures. Most of these failures occurred in regions of strong ocean currents - the Kuroshio Current, the Loop Current of the Gulf of Mexico, and the Gulf Stream. Stations in the western North Pacific Ocean experienced prolonged outages because of the great distances from staging areas and persistent stormy weather and their proximity to major storm tracks. However, in 2007 the mooring and system at station 42407, in the Caribbean, had exceeded design specifications by weathering the passage of Hurricane Dean, when it was a Category 4 hurricane. In the spring and summer of 2009, a series of ambitious service cruises will return the network to nearly full operating capability. Focusing on ways to reduce future outages, NDBC undertook a number of engineering initiatives, including an intensive investigation into the mooring failures and deployed several new mooring types for evaluation and obtained warehouse space in Guam to reduce logistical requirements.

In response to requirements from the US Tsunami Warning Centers (TWC) – the Pacific Tsunami Warning Center, Ewa Beach, Hawai'i and the West Coast/Alaska Tsunami Warning Center, Palmer, Alaska - the 2009 deployments included new firmware that provided the TWCs more control and improved initiating event or rapid reporting mode. Previous firmware versions added an artificial 100 mm to the estimated water-column height in order to initiate and indicate rapid reporting mode by command from the TWCs. Command-initiated modes are now distinguished from on-board-initiated modes by new message identifiers. NDBC made changes to the electronics to reduce the number of false event modes that have made up about a third of all event mode initiations. The changes will also prevent the corruption of transmitted data caused by feedback during the acoustic transmissions.

In 2009, NDBC completed the initial field test and evaluation of its new Standard Buoy, configured for tsunameter operations and its first operational use at Station 46412. The Standard Buoy will provide a common, lower-cost platform that can be used interchangeably with NDBC's other buoy programs – Weather and Oceanographic Platforms (WxOP) and the Tropical Atmosphere Ocean (TAO) Array Buoys. In addition, Standard Buoys will have the capability to provide multi-purpose capabilities, such as making meteorological measurements at tsunameter stations. During the past year, NOAA added the tsunameter messages to its NOAAPORT broadcast system that provides NOAA's environmental data and information to external users through a commercial provider.

I. INTRODUCTION

The US operational Deep-Sea network of tsunameters has grown from six stations confined to the Northeast Pacific Ocean to 39 stations that span the Pacific and the western Atlantic oceans, Gulf of Mexico, and Caribbean Sea [Fig. 1]. The tsunameters employ the technology of the second generation Deep-ocean Assessment and Reporting of Tsunamis (DART® II). The National Oceanic and Atmospheric Administration's (NOAA) National Data Buoy Center (NDBC) is responsible for operating and maintaining the network and its technology. Data from the stations play a critical role in the tsunami warning system that includes the Tsunami Warnings Centers (TWC) – the Pacific Tsunami Warning Center (PTWC), Ewa Beach, Hawai'i and the West Coast/Alaska Tsunami Warning Center (WC/ATWC), Palmer, Alaska. The TWCs use the data to detect the generation of tsunamis and their amplitudes.

II. TECHNOLOGY

The DART® II systems consist of a Bottom Pressure Recorder (BPR) on the seafloor that records the absolute pressure and the temperature near the sea-floor and transfers data to a surface buoy that acts as transceiver between the buoy and NDBC (Fig. 2). The BPR samples at 15-second intervals and creates estimated water-column heights from the temperature-corrected pressure by multiplying by 670 mm per pound per square inch, absolute. The full-resolution 15-second data are saved to a flash card. The BPR contains a tsunami detection algorithm. The algorithm does a forward prediction of the latest measurement based on past

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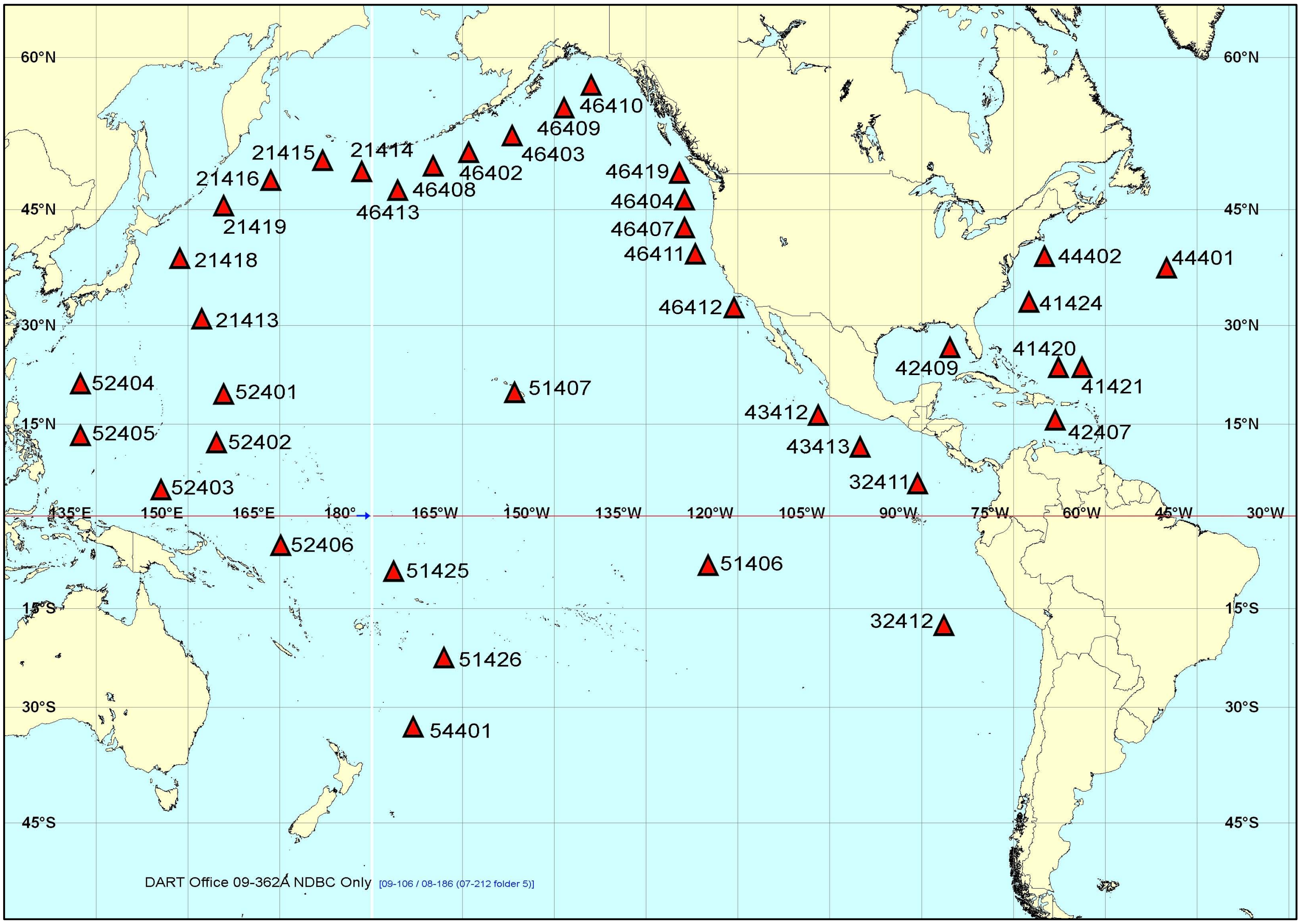

Fig. 1 Tsunameter stations identified by their WMO Station Index Numbers.

data. If the absolute difference between the predicted value and the measurement exceeds a configurable threshold (usually 30 mm), then the BPR goes into Event or rapid reporting Mode.

When not in Event Mode, the BPR is considered in Standard Mode and subsamples the full 15-second data record at 15-minute intervals then sends them to the buoy every hour. The buoy collects six hours worth of these 15-minute data and transmits them to NDBC via Iridium satellite. Standard Mode data serves as an indicator of the health of the system and are used for harmonic analysis in order to remove the tidal signal from the tsunameter records to provide a more accurate estimate of the amplitude of a tsunami. The buoy buffers data so that in the event communications between the buoy and NDBC are interrupted, the data will be sent to NDBC when communications are restored.

In Event Mode, the BPR sends an initial four minutes of the 15-second data, followed by four hours of one-minute average data, initially at overlapping 8-minute intervals. Event Mode is usually initiated by the seismic signal of an earthquake. Any resulting tsunami will then be detected in the one-minute averaged data (Fig 3).

The BPR can be deployed to depths of 6000 meters. Data are sent from the BPR to the buoy via underwater acoustic transmission and from the buoy to NDBC via commercial satellite communications. The system has two-way communications that can be used to initiate Event Mode in anticipation of a tsunami passage or retrieve one-hour portions of the full resolution 15-second data from the BPR in real-time.

III. Data Management

NDBC is responsible for managing the data for the network. Data takes three minutes or less to go from the BPR to the TWCs. About 50 seconds of that is to reach the NDBC server from the BPR. NDBC encapsulates the messages received from the buoy into bulletins for distribution to the TWCs and the international tsunami warning communities [1]. NDBC assigns each station a

five-digit World Meteorological Organization Station Index Number. Data from stations in the Atlantic Ocean are distributed under the SZNT01 KWNB bulletin header, from the North Pacific Ocean under the SZPN01 KWNB, from the South Pacific Ocean under SZPS01 KWNB, and from the Indian Ocean under SZIO01 KWNB. In the past year, the bulletins became available on NOAAPORT, which is a broadcast system that provides a one-way broadcast communication of NOAA environmental data and information in near-real time to NOAA and external users.

Real-time data are available on the NDBC webpage (http://www.ndbc.noaa.gov) in text formats and netCDF format via NDBC's OPeNDAP/DODS server. Normally NDBC recovers the BPRs every two years and sends the recorded data to the National Geophysical Data Center, Boulder, CO for permanent archive (http://www.ngdc.noaa.gov/hazard/DARTData.shtml).

In 2009, NDBC fielded a firmware change (Version 2.78) that provided the TWCs with the capability to interrupt on-going events and re-trigger the system in order to extend the rapid reporting of Event Mode. The firmware also introduced new message types to indicate manual triggers. Previously, manual triggers were indicated by the addition of 100 mm to the water-column heights of the first few minutes of an Event. NDBC fielded a new Command Console that provides improved scheduling of Manual triggers to take advantage of the listening windows of the buoy's satellite receivers, and tracks the status of the Commands to prevent needless re-triggering.

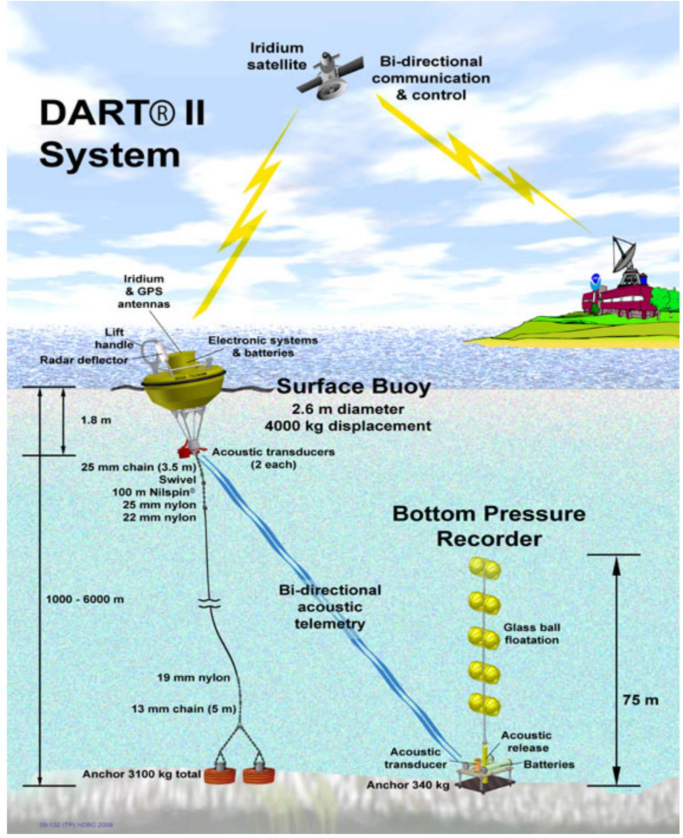

Fig. 2. Tsunameter Technology

IV. System Performance

NDBC monitors two statistics to gauge system performance – data availability and false alarm (event) rate. NDBC measures data availability by the number of measurements returned to NDBC versus the number of expected measurements. The overall network average is the average of the station averages. The first full-year and four months of operation of the 39-station network from April 2008 through July 2009 showed a data availability rate of 78%. The data availability goal is 80%. Previous studies showed better than 85% for DART® II stations in the period September 2005 through March 2007 [2] and for all stations for the years 2006, 2007, and 2008 [3]. Low data availability rates were symptomatic in the northwest Pacific Ocean, Gulf of Mexico, and the Western Atlantic Ocean. Mooring casualties during the winter months of 2008 and 2009 accounted for the majority of the failures. Compounding the problem is the high winds and seas of the higher latitudes in the winter that prevented service cruises, thus prolonging outages in those areas. The mooring casualties generally coincided with the strong current regimes of the Kuroshio Current (northwest Pacific Ocean), the

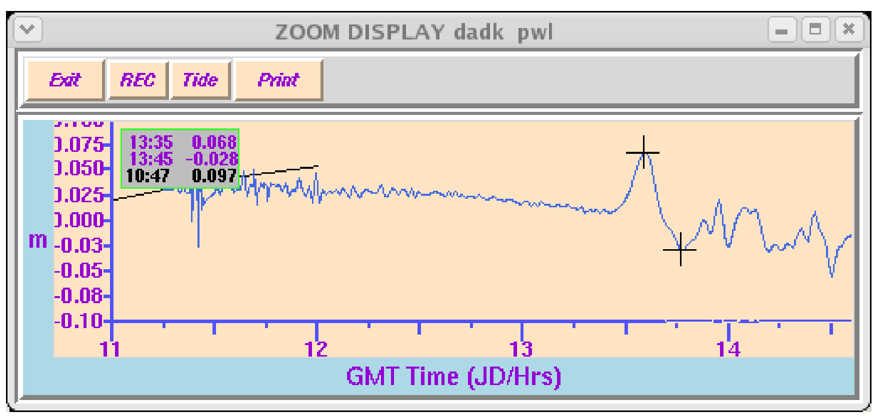

Fig. 3 De-tided water-column height at Station 46413, near the Aleutian Islands, associated with November 2006, Kuril Islands earthquake. 9.5 minutes after Earthquake, arrival of Seismic Signal (sawtooth signal to the left) triggers 46413 into Event Mode. Then two hours later 0.10 m (indicated by cross-hairs to the right) tsunami arrives at the station and propagates to Crescent City CA where 0.88 m tsunami impacts the marina.

Loop Current (Gulf of Mexico), the Gulf Stream (western North Atlantic) and the North Equatorial Current (north of Puerto Rico). Data availability per station is shown below (Fig. 4). However in August 2007, Hurricane Dean, a Category 4 hurricane passed within 30 km of Station 42407 in the Caribbean and 42407 remained moored and continued to transmit seafloor data [4].

NDBC is in the process of undertaking a series of comprehensive service cruises during the spring, summer, and early fall of 2009 to restore stations. By mid-August 2009, data availability exceeds 95%. NDBC engineers are conducting investigations into the mooring failures examining the effects of inaccurate bathymetry, currents, vandalism, and fish bite [5]. NDBC has also established a logistical facility in Guam that will potentially reduce outage times of the stations in the western Pacific by having a ready source of equipment and spare parts for deployment.

Events are considered false if there is no associated seismic activity or manual trigger. The false alarm rate had been on the order of 25% (16 of 62) [2], but for the period April 2008 through July 2009, the false alarm rate was on the order of 50%. Ironically, this is due to the upgrade of stations from the first generation (DART® I) to DART® II systems in which some of the systems were prone to electronic feedback from the acoustic modems that then tripped the tsunami detection algorithm. The electronic feedback would persist and cause a cascade of false events. The probable cause of the electronic feedback has been identified and systems are now being deployed with corrected electronics.

V. SYSTEM PLANS

NDBC will upgrade the remaining stations with the Version 2.78 firmware. NDBC is investigating the use of the Easy-To-Deploy (ETD) DART® systems [6] and autonomous vehicles to provide quick, short-term response for failed or degraded systems. The 2009 service cruises will recover a number of the systems with failed moorings for engineering analysis.

NDBC is testing and evaluating its Standard Buoy [7] for use in the tsunameter systems. The first operational test and evaluation is being conducted at Station 46412 off of Southern California is showing encouraging results. The Standard Buoy will become the basis for all NDBC moored buoy programs –Weather and Oceanographic Platforms (WxOP), Tropical Atmosphere Ocean Array (TAO), as well as the tsunameter network. In addition, the Standard Buoy will provide a multi-purpose platform that would allow, for example, the tsunameter buoy to make meteorological measurements.

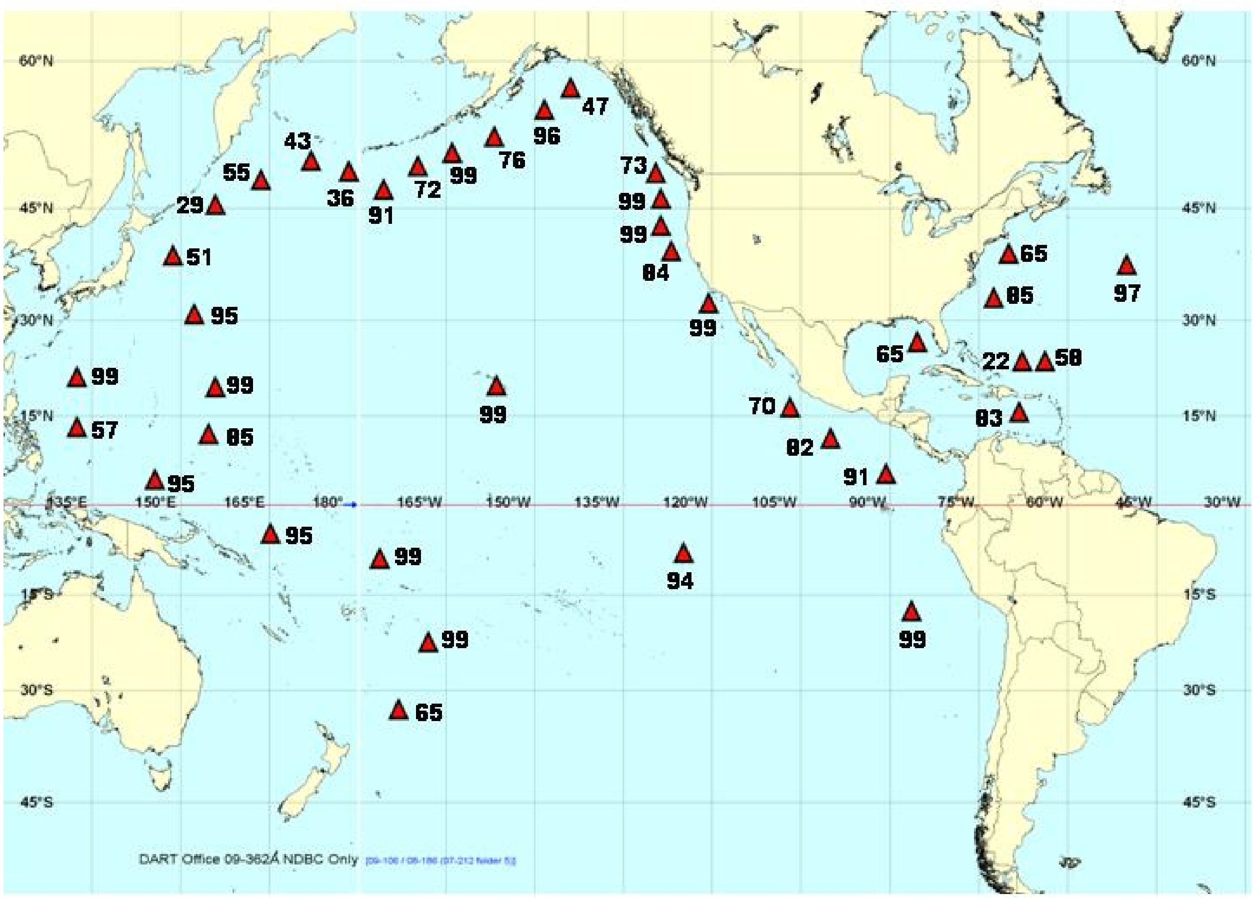

Fig. 4 Data Availability Percentages for each tsunameter station for the period April 2008 – July 2009.

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